

# Probe of $CP$ Violation in $e^+e^- \rightarrow t\bar{t}$ Near Threshold\*

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## Abstract

We report our theoretical study on how to probe the anomalous  $CP$ -violating couplings of the top quark in the  $t\bar{t}$  region at future  $e^+e^-$  linear colliders. We focus on the unique role of the  $t\bar{t}$  threshold region.

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# 1 Introduction

In this article we report our recent theoretical study [1] on how to probe  $CP$  violation in the top quark sector at future  $e^+e^-$  linear colliders in the  $t\bar{t}$  threshold region.

Recently studies of various properties of the top quark have been started at Tevatron. The detailed properties will be investigated further in future experiments at LHC and at future  $e^+e^-$  linear colliders. Among various interactions of the top quark, testing the  $CP$ -violating interactions is particularly interesting due to following reasons:

- Within the Standard Model (SM),  $CP$ -violation in the top quark sector is extremely small. [The electric-dipole-moment (EDM) of a quark is induced first at three-loop level [2].] If any  $CP$ -violating effect is detected in the top quark sector in a near-future experiment, it immediately signals new physics.
- There can be many sources of  $CP$ -violation in models that extend the SM, such as supersymmetric models, Leptoquark models, multi-Higgs-doublet models, Extra-dimensions, etc. Besides, the observed baryon asymmetry in the Universe suggests existence of  $CP$  violating mechanisms beyond the SM.
- In relatively wide class of models beyond the SM,  $CP$  violation emerges especially sizably in the top quark sector. A typical example is shown in Fig. 1.

Let us state the set-ups of our analysis. We consider  $CP$ -violating interactions of top quark with  $\gamma$ ,  $Z$ , and  $g$ . In particular, we consider the lowest dimension  $CP$ -odd effective operators:

$$\mathcal{L}_{CP\text{-odd}} = -\frac{ed_{t\gamma}}{2m_t}(\bar{t}i\sigma^{\mu\nu}\gamma_5 t)\partial_\mu A_\nu - \frac{g_Z d_{tZ}}{2m_t}(\bar{t}i\sigma^{\mu\nu}\gamma_5 t)\partial_\mu Z_\nu - \frac{g_s d_{tg}}{2m_t}(\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t)\partial_\mu G_\nu^a, \quad \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu], \quad (1)$$

where  $e = g_W \sin \theta_W$  and  $g_Z = g_W / \cos \theta_W$ . These represent the interactions of  $\gamma$ ,  $Z$ ,  $g$  with

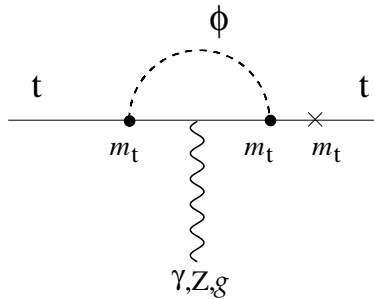


Figure 1: In two-Higgs-doublet models, a neutral Higgs boson  $\phi$  can violate  $CP$  through the Yukawa interaction. The top quark EDM is induced by an exchange of  $\phi$  at one loop and is proportional to  $m_t^3$ . One power of  $m_t$  is necessary to flip chirality; extra two powers come from the Yukawa interaction. Since this is a one-loop effect, it is much larger than the SM EDM; since it is proportional to  $m_t^3$ , it is strongly enhanced in comparison to the other quarks' EDMs.

		$\delta d_{tg}$	$\delta d_{t\gamma}$	$\delta d_{tZ}$
LHC (10 fb <sup>-1</sup> )		10 <sup>-2</sup> – a few $\times 10^{-3}$	-	-
$e^+e^-$ LC (50 fb <sup>-1</sup> )	open top	$\mathcal{O}(1)$	10 <sup>-1</sup> – a few $\times 10^{-2}$	10 <sup>-1</sup> – a few $\times 10^{-2}$
	$t\bar{t}$ threshold	10 <sup>-1</sup>	10 <sup>-1</sup>	10 <sup>-1</sup>

Table 1: The results of studies of sensitivities to the anomalous couplings expected in future experiments. For  $e^+e^-$  linear colliders (LC), “open top” denotes the results of studies performed at  $\sqrt{s} = 500$  GeV. These results are taken from [3]-[19].

the EDM, Z-EDM, chromo-EDM of top quark, respectively.\* Each of the interactions has  $C = +1$  and  $P = -1$ . As stated, the SM contributions to these couplings are extremely small,  $d_{t\gamma}^{(\text{SM})}, d_{tZ}^{(\text{SM})}, d_{tg}^{(\text{SM})} \sim 10^{-14}$ . Since we will not be able to detect them in near-future collider experiments, we neglect the SM contributions below. Our concern is in the anomalous couplings which are induced from some new physics. We assume that generally the couplings  $d_{t\gamma}, d_{tZ}, d_{tg}$  are complex where their imaginary parts may be induced from some absorptive processes.

Many of the readers would be interested in the sensitivities to these couplings expected in future experiments. In Table 1 we summarize the results of the sensitivity studies performed so far, including the results of our present study. We may compare the sensitivities of experiments in the  $t\bar{t}$  threshold region at  $e^+e^-$  colliders with others. The sensitivities to  $d_{t\gamma}$  and  $d_{tZ}$  are comparable to those attainable in the open-top region at  $e^+e^-$  colliders. The sensitivity to  $d_{tg}$  is worse than that expected at a hadron collider but exceeds the sensitivity in the open-top region at  $e^+e^-$  colliders.

From this comparison one may find that our study at  $t\bar{t}$  threshold has little impact on the study of  $CP$  violation and is not very interesting. The present author, however, has a slightly different physics interest personally. Although admittedly it is better to have higher sensitivities to the anomalous couplings  $d_{tg}, d_{t\gamma}, d_{tZ}$ , at the moment we do not know the sizes of these couplings. Therefore, I am interested more in the following questions than merely in achievable sensitivities: When any of the couplings happens to be sizable enough to be detected in some experiment, through what intriguing phenomena can we detect the anomalous couplings? And how can we extract as much information on the couplings as possible? In these respects, the  $t\bar{t}$  threshold region has fairly rich physics contents. I would like to describe our investigations from this viewpoint below. So, please imagine a situation where any of the couplings happens to be of order 10% or larger and see what we can learn in that case.

## 2 $t\bar{t}$ Threshold

### 2.1 Unique aspects

When studying  $CP$  violation of the top quark, unique aspects of the  $t\bar{t}$  threshold region are:

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\* The magnitudes of these EDMs are given by  $ed_{t\gamma}/m_t, g_Z d_{tZ}/m_t, g_s d_{tg}/m_t$ , respectively.  $d_{t\gamma} = 1$  corresponds to  $e/m_t \sim 10^{-16}$  e cm, etc.

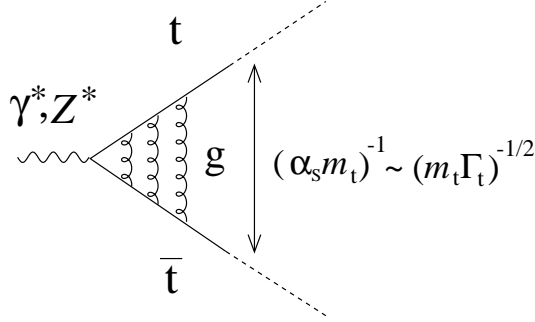


Figure 2: The time evolution of the  $t\bar{t}$  system within the SM.

- The QCD interaction is enhanced in this region, hence the cross section is sensitive to the top-gluon ( $tg$ ) couplings. We can study anomalous  $tg$  couplings in a clean environment in comparison to hadron colliders.
- In certain models (e.g. those in which a neutral Higgs boson is exchanged between  $t$  and  $\bar{t}$  [20]), induced top quark EDM and  $Z$ -EDM are enhanced near the  $t\bar{t}$  threshold.
- Since top quarks are produced almost at rest, one can reconstruct the spin information of top quarks from distributions of their decay products without solving detailed kinematics.

## 2.2 Time evolution of the $t\bar{t}$ system

Let us first review the time evolution of  $t$  and  $\bar{t}$ , pair-created in  $e^+e^-$  collision just below threshold, within the SM (Fig. 2). They are created close to each other at a relative distance  $r \sim 1/m_t$  and then spread apart non-relativistically. When their relative distance becomes of the order of the Bohr radius,  $r \sim (\alpha_s m_t)^{-1}$ , they start to form a Coulombic boundstate. When the relative distance becomes  $r \sim (m_t \Gamma_t)^{-1/2}$ , where  $\Gamma_t$  is the decay width of top quark, either  $t$  or  $\bar{t}$  decays via electroweak interaction, and accordingly the boundstate decays. Numerically these two scales have similar magnitudes,  $(\alpha_s m_t)^{-1} \sim (m_t \Gamma_t)^{-1/2}$ , and are much smaller than the hadronization scale  $\sim \Lambda_{\text{QCD}}^{-1}$ . Since gluons which have wavelengths much longer than the size of the  $t\bar{t}$  system cannot couple to this color singlet system, the strong interaction participating in the formation of the boundstate is dictated by the perturbative domain of QCD. Due to this reason, we are able to compute the amplitude from the first principles with order 5% accuracy or better, even though the QCD boundstates are involved.<sup>†</sup> The spin and  $PC$  of the dominantly produced boundstate are  $J^{PC} = 1^{--}$ . Inside this boundstate:  $t$  and  $\bar{t}$  are in the  $S$ -wave state ( $L = 0$ ); the spins of  $t$  and  $\bar{t}$  are aligned to each other and pointing to  $e^-$  beam direction  $|\uparrow\uparrow\rangle$  or to  $e^+$  beam direction  $|\downarrow\downarrow\rangle$  or they are in a linear combination of the two states ( $S = 1$ ).

<sup>†</sup> At the moment only one exception is the normalization of the total  $t\bar{t}$  cross section, where we still have 10–15% theoretical uncertainty.

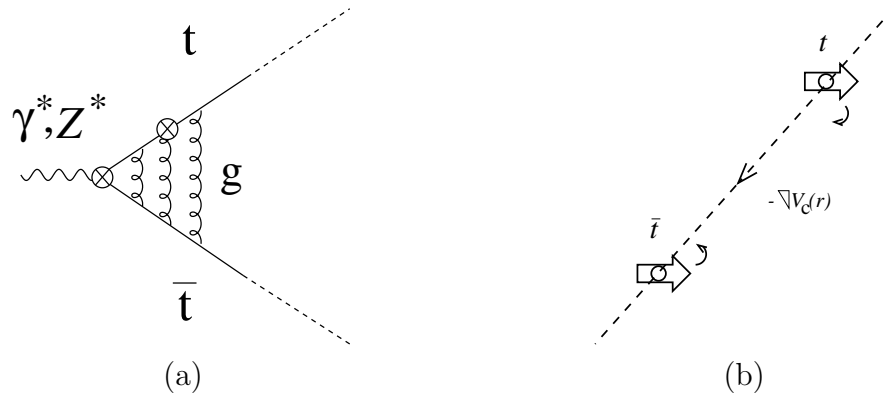


Figure 3: (a) The time evolution of the  $t\bar{t}$  system when the effects of  $\mathcal{L}_{CP\text{-odd}}$  are included.  $\otimes$  represent the anomalous couplings. (b) The potential  $V_{CP\text{-odd}}$  tends to align the  $t$  spin in the direction of the color-electric field and the  $\bar{t}$  spin in the opposite direction.

Now let us consider effects of the anomalous interactions eq. (1) on the time evolution of the  $t\bar{t}$  system (Fig. 3(a)).  $CP$ -violation originating from the  $t\gamma$  or  $tZ$  coupling occurs at the stage of the pair creation, i.e. when  $t$  and  $\bar{t}$  are very close to each other. The generated boundstate has  $J^{PC} = 1^{+-}$ , so  $t$  and  $\bar{t}$  are in the  $P$ -wave ( $L = 1$ ) and spin-0 state  $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$ . On the other hand,  $CP$ -violation originating from the  $tg$  coupling takes place after the boundstate formation when multiple gluons are exchanged between  $t$  and  $\bar{t}$ , i.e. when  $t$  and  $\bar{t}$  are separated at a distance of the Bohr radius. The anomalous top-gluon coupling generates effectively a spin-dependent potential between  $t$  and  $\bar{t}$

$$V_{CP\text{-odd}} = \frac{d_{tg}}{m_t} (\mathbf{s}_t - \bar{\mathbf{s}}_t) \cdot \nabla V_C(r). \quad (2)$$

Here,  $\mathbf{s}_t$  and  $\bar{\mathbf{s}}_t$  denote the spins of non-relativistic  $t$  and  $\bar{t}$ , respectively;  $V_C(r) = -C_F\alpha_s/r$  is the Coulomb potential with the color factor  $C_F = 4/3$ . When  $d_{tg} > 0$ , the potential  $V_{CP\text{-odd}}$  tends to align both chromo-EDMs in the direction of chromo-electric field, or, align  $\bar{\mathbf{s}}_t$  in the direction of  $\mathbf{r} = \mathbf{r}_t - \mathbf{r}_{\bar{t}}$  and  $\mathbf{s}_t$  in the direction of  $-\mathbf{r}$ ; see Fig. 3(b). Therefore, first the boundstate is formed in  $J^{PC} = 1^{--}$  ( $L = 0$  and  $S = 1$ ) state and after interacting via the potential  $V_{CP\text{-odd}}$  it turns into  $J^{PC} = 1^{+-}$  ( $L = 1$  and  $S = 0$ ) state, i.e. the  $t$  and  $\bar{t}$  spins are aligned into antiparallel directions.

We can disentangle the effects of the three couplings,  $d_{t\gamma}$ ,  $d_{tZ}$ ,  $d_{tg}$ , on the amplitude using the differences in the dependences on the energy and  $e^\pm$  polarization in the threshold region. Firstly when the c.m. energy is raised the  $CP$ -violating effects due to  $d_{t\gamma}$  and  $d_{tZ}$  increase proportionally to the velocity of the top quark, since these effects are induced directly by the dimension-five operators. On the other hand, the effect of  $d_{tg}$  does not increase so rapidly. The enhancement of the  $tg$ -coupling due to multiple exchanges of gluons will be lost when the energy is raised and  $t$  and  $\bar{t}$  spread apart quickly without forming boundstates. Secondly, one may vary the relative weight of the photon-induced  $CP$ -violating effect and the  $Z$ -induced effect by varying the  $e^\pm$  longitudinal polarization. This is because  $e_L$  and  $e_R$  couple differently to  $\gamma$  and  $Z$ , and the relative weight of virtual  $\gamma$  and  $Z$  changes.

## 2.3 $CP$ -odd observables

Which  $CP$ -odd observables are sensitive to the  $CP$ -violating couplings  $d_{t\gamma}$ ,  $d_{tZ}$ ,  $d_{tg}$ ? For the process  $e^+e^- \rightarrow t\bar{t}$ , we may conceive of following expectation values of kinematical variables for  $CP$ -odd observables:

$$\begin{aligned} & \langle (\mathbf{p}_e - \bar{\mathbf{p}}_e) \cdot (\mathbf{s}_t - \bar{\mathbf{s}}_t) \rangle, \\ & \langle (\mathbf{p}_t - \bar{\mathbf{p}}_t) \cdot (\mathbf{s}_t - \bar{\mathbf{s}}_t) \rangle, \\ & \langle [(\mathbf{p}_e - \bar{\mathbf{p}}_e) \times (\mathbf{p}_t - \bar{\mathbf{p}}_t)] \cdot (\mathbf{s}_t - \bar{\mathbf{s}}_t) \rangle, \end{aligned} \quad (3)$$

where the spins and momenta are defined in the c.m. frame. (The initial state is  $CP$ -even if we assume the SM interactions of  $e^\pm$  with  $\gamma$  and  $Z$ .) The above quantities are the three components of the difference of the  $t$  and  $\bar{t}$  spins. One may easily confirm the  $CP$  transformations of the above observables: e.g.  $(\mathbf{p}_t - \bar{\mathbf{p}}_t) \xrightarrow{C} (\bar{\mathbf{p}}_t - \mathbf{p}_t) \xrightarrow{P} (-\bar{\mathbf{p}}_t + \mathbf{p}_t)$ . One might say (in a somewhat oversimplified way) that in the SM the  $t$  and  $\bar{t}$  spins are parallel to each other, so the SM contributions drop in the difference  $\mathbf{s}_t - \bar{\mathbf{s}}_t$ , whereas the  $t$  and  $\bar{t}$  spins become antiparallel to each other by the effects of  $\mathcal{L}_{CP\text{-odd}}$ , so they remain in  $\mathbf{s}_t - \bar{\mathbf{s}}_t$ . Thus, we want to measure the difference of the spins of  $t$  and  $\bar{t}$ . It is equivalent to measuring the difference of the polarization vectors of  $t$  and  $\bar{t}$ . All other  $CP$ -odd observables for  $e^+e^- \rightarrow t\bar{t}$  are bilinear in  $\mathbf{s}_t$  and  $\bar{\mathbf{s}}_t$ . Since analyses of spin correlations are complicated, we focus on the difference of the polarization vectors.

Practically we can measure the  $t$  and  $\bar{t}$  polarization vectors efficiently using  $\ell^\pm$  angular distributions. It is known that the angular distribution of the charged lepton  $\ell^+$  from the decay of top quark is maximally sensitive to the top quark polarization vector. In the rest frame of top quark, the  $\ell^+$  angular distribution is given by [21]

$$\frac{1}{\Gamma_t} \frac{d\Gamma(t \rightarrow b\ell^+\nu)}{d\cos\theta_{\ell^+}} = \frac{1 + P \cos\theta_{\ell^+}}{2} \quad (4)$$

at tree level, where  $P$  is the top quark polarization and  $\theta_{\ell^+}$  is the angle of  $\ell^+$  measured from the direction of the top quark polarization vector. Indeed the  $\ell^+$  distribution is ideal for extracting  $CP$ -violation in the  $t\bar{t}$  production process; the above angular distribution is unchanged even if anomalous interactions are included in the  $t\bar{t}W$  decay vertex, up to the terms linear in the decay anomalous couplings and within the approximation  $m_b = 0$  [22]. Therefore, if we consider the average of the lepton direction, for instance, we may extract the top quark polarization vector efficiently:

$$\langle \mathbf{n} \cdot \mathbf{n}_\ell \rangle_{\text{Lab}} \simeq \frac{1}{3} \mathbf{n} \cdot \mathbf{P}. \quad (5)$$

The average is to be taken at the top quark rest frame, but in the threshold region, we may take the average in the laboratory frame barely without loss of sensitivities to the anomalous couplings.

## 2.4 $t$ and $\bar{t}$ polarization vectors

The polarization vectors of  $t$  and  $\bar{t}$  are defined from the production cross section of a  $t\bar{t}$  pair in the threshold region. The cross section, where  $(t, \bar{t})$  have momenta  $(\mathbf{p}_t, -\mathbf{p}_t)$  and the spins  $+\frac{1}{2}$  along the quantization axes  $(\mathbf{s}_t, \bar{\mathbf{s}}_t)$  in the c.m. frame, is given by

$$\frac{d\sigma(\mathbf{s}_t, \bar{\mathbf{s}}_t)}{d^3\mathbf{p}_t} = \frac{d\sigma}{d^3\mathbf{p}_t} \frac{1 + \mathbf{P} \cdot \mathbf{s}_t + \bar{\mathbf{P}} \cdot \bar{\mathbf{s}}_t + (\mathbf{s}_t)_i (\bar{\mathbf{s}}_t)_j \mathbf{Q}_{ij}}{4}. \quad (6)$$

Here,  $|\mathbf{s}_t| = |\bar{\mathbf{s}}_t| = 1$ . On the right-hand-side,  $d\sigma/d^3\mathbf{p}_t$  represents the production cross section when the spins of  $t$  and  $\bar{t}$  are summed over.  $\mathbf{P}$  and  $\bar{\mathbf{P}}$  denote, respectively, the polarization vectors of  $t$  and  $\bar{t}$ .

According to the above definition we computed the polarization vectors. The SM contributions to the polarization vectors are same for  $t$  and  $\bar{t}$ , while the contributions from  $\mathcal{L}_{CP\text{-odd}}$  are opposite in sign:

$$\mathbf{P} = \mathbf{P}_{\text{SM}} + \delta\mathbf{P}, \quad \bar{\mathbf{P}} = \mathbf{P}_{\text{SM}} - \delta\mathbf{P}. \quad (7)$$

It is convenient to express  $\delta\mathbf{P}$  in components:

$$\delta\mathbf{P} = \delta P_{\parallel} \mathbf{n}_{\parallel} + \delta P_{\perp} \mathbf{n}_{\perp} + \delta P_{\text{N}} \mathbf{n}_{\text{N}}, \quad (8)$$

where the orthonormal basis is defined from the  $e^-$  beam direction and the top quark momentum direction as

$$\mathbf{n}_{\parallel} = \frac{\mathbf{p}_e}{|\mathbf{p}_e|}, \quad \mathbf{n}_{\text{N}} = \frac{\mathbf{p}_e \times \mathbf{p}_t}{|\mathbf{p}_e \times \mathbf{p}_t|}, \quad \mathbf{n}_{\perp} = \mathbf{n}_{\text{N}} \times \mathbf{n}_{\parallel}. \quad (9)$$

Then the  $CP$ -odd contributions are given by

$$\delta P_{\parallel} = 0, \quad (10)$$

$$\delta P_{\perp} = \text{Im} \left[ d_{tg} B_{\perp}^g \left( \frac{D}{G} \right) + d_{t\gamma} B_{\perp}^{\gamma} \left( \frac{F}{G} \right) + d_{tZ} B_{\perp}^Z \left( \frac{F}{G} \right) \right] \left( \frac{p_t}{m_t} \right) \sin \theta_t, \quad (11)$$

$$\delta P_{\text{N}} = \text{Re} \left[ d_{tg} B_{\text{N}}^g \left( \frac{D}{G} \right) + d_{t\gamma} B_{\text{N}}^{\gamma} \left( \frac{F}{G} \right) + d_{tZ} B_{\text{N}}^Z \left( \frac{F}{G} \right) \right] \left( \frac{p_t}{m_t} \right) \sin \theta_t. \quad (12)$$

Here,  $B_{\perp}^X$  and  $B_{\text{N}}^X$  denote combinations of the electroweak couplings of  $e^-$  and  $t$  as well as of  $e^{\pm}$  beam polarization.  $D$ ,  $F$  and  $G$  denote the QCD Green functions which incorporate the boundstate effects.

In Fig. 4 we examine the electroweak coefficients  $B_i^X$ 's. They are given as a function of the polarization parameter of the initial  $e^{\pm}$  beams

$$\chi = \frac{P_{e^+} - P_{e^-}}{1 - P_{e^+} P_{e^-}}. \quad (13)$$

If the positron beam is unpolarized ( $P_{e^+} = 0$ ),  $\chi = -P_{e^-}$ . Typical sizes of all the coefficients  $B_i^X$ 's are order one. We also see that their dependences on the beam polarizations are different.

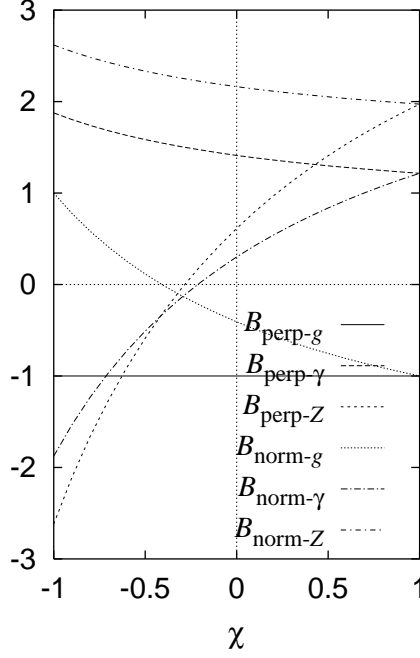


Figure 4: The electroweak coefficients  $B_i^X$ 's for  $\delta P_\perp$  and  $\delta P_N$  vs. the initial  $e^\pm$  polarization parameter  $\chi$ . In the figure,  $B_{\text{para}} = B_\parallel$ ,  $B_{\text{perp}} = B_\perp$ ,  $B_{\text{norm}} = B_N$ .

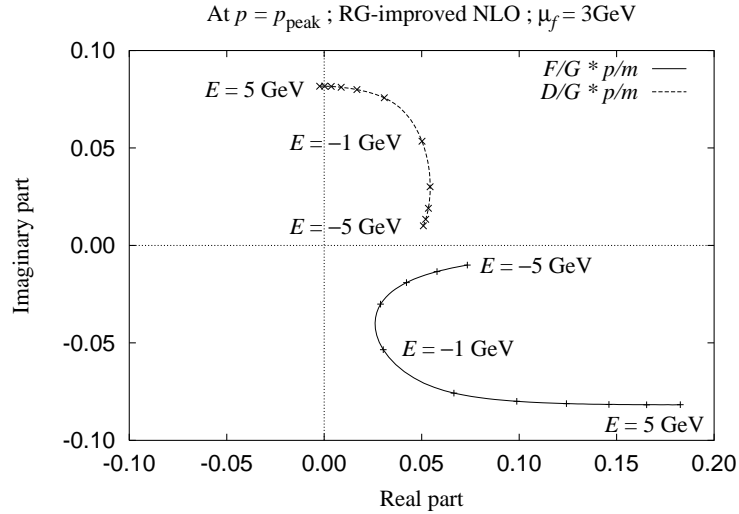


Figure 5: The ratios of the QCD Green functions times the velocity of top quark evaluated at the peak momentum  $p_{\text{peak}}$  of the momentum distribution. These are plotted on a complex plane as  $E = \sqrt{s} - 2m_t$  is varied.

Next we examine the QCD factor in Fig. 5. The ratios of the Green functions together with the top quark velocity ( $\beta = p_t/m_t$ ),  $\beta D/G$  and  $\beta F/G$ , are shown on a complex plane. These are plotted as a function of the energy  $E = \sqrt{s} - 2m_t$  alone by choosing the top momentum to be the typical momentum at a fixed energy. As we raise the energy, the magnitude of the QCD factor associated with the  $t\gamma$  and  $tZ$  couplings,  $|\beta F/G|$ , increase proportionally to  $\beta$ . On the other hand, the magnitude of the QCD factor associated with the  $tg$  coupling,  $|\beta D/G|$ , does not change very much. We see that the size of  $|\beta F/G|$  is 5–20% while the size of  $|\beta D/G|$  is 5–10%. Also it can be seen that the strong phases are quite sizable and change rapidly with energy. It is the characteristics of the  $t\bar{t}$  boundstates that these QCD factors can be computed reliably from the first principles.

### 3 Conclusions

In this work we studied how to probe the anomalous  $CP$ -violating couplings of the top quark with  $\gamma$ ,  $Z$  and  $g$  in the  $t\bar{t}$  threshold region at future  $e^+e^-$  colliders. The sensitivities to the anomalous couplings are given and compared with other future experiments in Table 1. Qualitatively, the characteristics of the  $t\bar{t}$  region are summarized as follows.

- (1) We can measure the three couplings  $d_{t\gamma}$ ,  $d_{tZ}$ ,  $d_{tg}$  simultaneously and we can disentangle each contribution.
- (2) We can measure the complex phases of the couplings  $d_{t\gamma}$ ,  $d_{tZ}$ ,  $d_{tg}$ . Since the strong phases can be modulated at our disposal, a single observable ( $\delta P_\perp$  or  $\delta P_N$ ) probes the phases of the couplings.
- (3) Typical sizes of components of the difference of the  $t$  and  $\bar{t}$  polarizations are given by

$$|\delta P_\perp|, |\delta P_N| \sim (5\text{--}20\%) \times (d_{t\gamma}, d_{tZ}, d_{tg}).$$

They can be extracted efficiently from the directions of charged leptons from decays of  $t$  and  $\bar{t}$ :

$$\langle \langle \mathbf{n} \cdot (\mathbf{n}_\ell + \bar{\mathbf{n}}_\ell) \rangle \rangle_{\mathbf{p}_t} \simeq \frac{2}{3} \mathbf{n} \cdot \delta \mathbf{P}.$$

We note that if one of the couplings is detected in the future, we would certainly want to measure the others in order to gain deeper understanding of the  $CP$ -violating mechanism. This is because one may readily think of various underlying processes which give different contributions to the individual couplings; see Fig. 6.

Regarding (1) and (2) above, QCD interaction is used as a controllable tool for the detection of the anomalous couplings. This would be the first trial to use QCD interaction for such a purpose without requiring any phenomenological inputs.

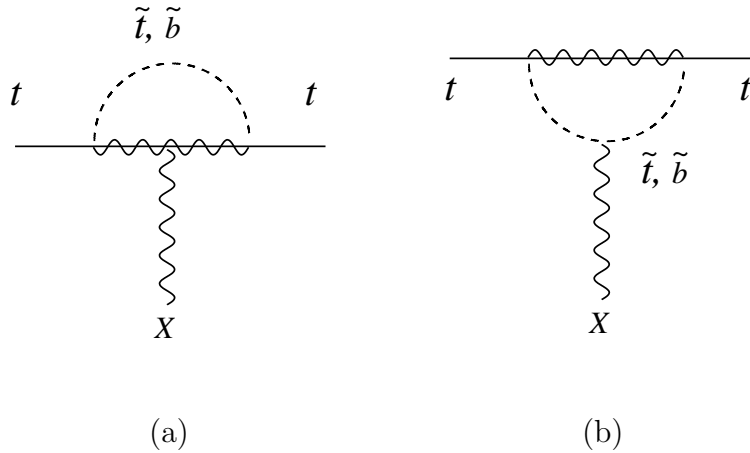


Figure 6: The diagrams which give rise to the top quark anomalous  $CP$ -violating couplings in a supersymmetric model. In diagram (a) only specific gaugino(s) couples to the gauge boson  $X = \gamma, Z$  or  $g$ . On the other hand, in diagram (b) all gauginos contribute.

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